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Flow control in time-varying, random supply chains

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ABSTRACT

This paper focuses on the logistics aspect of supply chain management. It proposes a randomized flow management algorithm for a time-varying, random, supply chain network. A constrained stochastic optimization problem that maximizes the profit function in terms of the long-run, time-average of the flows in the supply chain is formulated. The algorithm is distributed and based on queueing theory and stochastic Lyapunov analysis concepts. The long-run, time averages of the flows generated by the algorithm can get arbitrarily close to the solution of the aforementioned optimization problem. In support of the theoretical results, numerical simulations are also presented.

1. Introduction

Among many possible definitions, the supply chain can be defined as a network of interrelated activities of procurement, production, distribution, vendition, and consumption of one of more products (Zhang et al., 2003). Manufacturing is often outsourced around the world, with each component made in locations chosen for their expertise and low costs (Varkony, 2011). Consequently, today's supply chains are increasingly complex and rely on critical infrastructures such as roads, railways, and airports to move goods (Skulte and Wikerson, 2011), and therefore they exhibit the co-existence of operational optimization with operational vulnerability (Varkony, 2011). This was most recently and dramatically demonstrated in the aftermath of several accidents and natural disasters. For example, a fire in the Phillips Semiconductor plant in Albuquerque, New Mexico caused its major customer, Ericsson, to lose $400 million in potential revenues. Another example concerns the impact of Hurricane Katrina. This storm halted 10–15% of the total U.S. gasoline production, raising both domestic and overseas oil prices (Canadian Competition Bureau, 2006). More recently, the tragic earthquake of March 13, 2011, off the northeastern coast of Japan and the devastating tsunami that followed have shattered the nation, with immense loss of life and property. In addition, it brought uncertainty of the future, not the least of which is the expected decades-long impact of the nuclear reactors in Fukushima (Varkony, 2011).

As the world's economies become increasingly interconnected into a global economy, supply chain networks face many new types of risk, including natural disasters, political/social instability, cultural/communication inconsistency, exchange rate fluctuation, and local legislations (Behdani, 2011). These risks forced the supply chains' stakeholders to go beyond the operational optimization and to recognize the operational vulnerabilities of the supply chains and to underline their *time-varying* and *random* nature.

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This paper focuses on the *logistics* aspect of the supply chain management. Logistics plans, implements, and controls efficient and effective product storage and flows (forward/reverse). Logistics starts from the point of origin to the point of consumption, with the goal of meeting customer requirements (Blasgen, 2011). The paper addresses the flow management in a supply chain that exhibits stochastic behavior in both links and demands, and in addition it responds to the need for decentralized decisions as point out in (Chopra and Meindl, 2012). A randomized and decentralized algorithm for the management of the flow of the product in a time-varying, random supply chain aimed at maximizing the profit of a firm is proposed. Due to the random nature of the supply chain, the profit function is defined to be dependent on the (long-run, time) averages of the flows, since the flows are random processes. Hence, the optimization problem becomes stochastic. The approach for solving the optimization problem is as follows. First, the satisfiability of the supply chain' constraints is transformed into a stability condition on a set of queues associated with the supply chain's components. Second, a Lyapunov drift analysis technique is used to generate an algorithm that ensures the stability of the queues, and at the same time maximizes the profit function. This approach avoids the need of a realization of the stochastic parameters, as it is the case in a stochastic approximation approach. At each time instant, the algorithm produces decisions on the flows that are implementable (that is, take into account the current state of the supply chain). More importantly, the resulting long-run, time averages of the flows *get arbitrarily close* to the solution of the stochastic optimization problem. In addition, the algorithm *does not require knowledge of the probability distribution* of the random process that drives the supply chain and deals with both supply changes and demand variability. Furthermore, the *actions taken* by a specific decision maker are based only on a localized view of the state of the supply chain. This localized view consists of the state of all the links that have at one end the decision maker. In other words, *the algorithm is distributed*.

1.1. Related work

Supply chain networks face two types of uncertainties: (1) fluctuations in the demand side and (2) random disruptions in the supply side of the chain. The goal of supply chain management is to mitigate risks due to such uncertainties and efforts in the literature can consequently be classified according to the source(s) of uncertainty they consider.

For a long time, supply chain management research has focused on understanding and mitigating demand uncertainties, which are due to fluctuations both in the amount as well as in the variety of goods needed by the end users (see Lee et al., 1997; Gupta and Maranas, 2003; Hsu and Li, 2011 and the references therein). Fueled by numerous catastrophic events (natural disasters and intentional or unintentional human actions), in the last decade academics and practitioners have become increasingly interested in supply side disruptions (see Snyder et al., 2012, for a detailed literature review of supply chain disruptions). In reality, demand fluctuations and supply side disruptions occur concurrently and there have been a growing number of studies that attempt to simultaneously address both types of uncertainties (Baghalian et al., 2013). The present paper belongs to this category: we consider random demand fluctuations as well as random failures of the network's transportation links.

The mathematical tools used to model and analyze supply chain problems are also diverse and range from linear, nonlinear or mixed-integer programming (Aikens, 1985; Vidala and Goetschalck, 2001) to game theory (Nagarajan and Sosic, 2006; Nagurney, 2010; Qiang and Nagurney, 2009; Zhang et al., 2003). Due to the random nature of disruptions in the chain, stochastic models have been largely adopted in the literature (Lewis et al., 2013; Santoso et al., 2005; Lin, 2001; Chou et al., 2003). In this paper, we use a stochastic optimization model and propose a randomized and decentralized algorithm which can get arbitrary close to the optimal solution.

To optimize the supply chain, authors have also focused on different aspects of the chain. In inventory management, which has received a lot of attention (see Pontrandolfo et al., 2002; Qi et al., 2009; Lewis et al., 2013; Snyder et al., 2012, Sec. 6), the main goal "is to find optimal replenishment policy, which indicates *when, from whom*, and *how much* to order" (Snyder et al., 2012). Another considerable amount of work has been devoted to optimizing facility location (Baghalian et al., 2013; Lim et al., 2013; Snyder et al., 2012, Sec. 7). The goal here is to address the issue of *where* inventory should be stored and distributed. A third category, which has received much less attention, has focused on flow management (Hishamuddin et al., 2013; Unnikrishnan and Figliozzi, 2011). Flow management deals not only with how products are routed, but also, on how much product to send on each transport link. In this paper, we assume that the locations of the facilities are fixed and we are mainly concerned with product storage and flows. We consider a firm that is involved in the production, storage and distribution of a homogeneous products. Although our model may appear to be limited to only supply chains with a vertical integration, our decentralized algorithm can be applied to chains with different business entities, as long as the entities follow the strategies prescribed by the algorithm.

Compared to existing literature, our approach is unique by (1) the sources of uncertainties it considers, (2) the adopted model and the proposed solution method, and (3) the parameters of the chains it optimizes. Nevertheless, our approach intersects and complements several previous studies, while remaining fundamentally different. For instance, (Unnikrishnan and Figliozzi, 2011) proposes a stochastic optimization approach to study supply chain flow management with consideration of disruptions in the transportation links. However, the paper only considers supply side disruptions, while we are interested in both demand and supply side uncertainties. Furthermore, the proposed solution in (Unnikrishnan and Figliozzi, 2011) needs a centralized unit that has full knowledge of the chain. Our algorithm is decentralized and the actions taken by any decision maker depend only on its localized view of the state of the chain.